Stochastic Unified Multiple Access Protocol for Link-16

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ABSTRACT

Link-16 is the primary Department of Defense tactical data link. Although Link-16 is a very capable system, it has limitations as a dynamic networking asset. For example, Link-16 uses a preplanning process to assign transmission capacities to platforms. The process can take several weeks, and once a network is deployed, unplanned platforms cannot join the network. Also, the capacities dedicated to absent platforms cannot be reclaimed. Designed for small networks, the current Link-16 architecture cannot scale to support the large increase of platforms projected by the Navy. The Office of Naval Research (ONR)-sponsored Dynamic Reconfiguration of Link-16 project is developing the Stochastic Unified Multiple Access (SHUMA) protocol to address these important problems. SHUMA allows Link-16 platforms to fluidly enter and exit the theater; arbitrates the statistical sharing of the channel for better network performance; operates despite jamming, dynamic topology, transmission noises, and line-of-sight constraints; and scales to support a large number of units. This paper presents the salient features of the protocol.

INTRODUCTION

A multiple access protocol is a set of rules that governs how distributed units access a broadcast channel such as Link-16's. Our goal is to design a Link-16 multiple access protocol that is *simple* so that it can be implemented even in the older terminals; *robust* so that it can operate well despite jamming, transmission noises, dynamic topology, and line-of-sight (LOS) constraints; *scalable* so that it can support a large number of units; *adaptive* so that it can support the dynamic entry and exit of platforms; and *efficient*. The classical multiple access problem involves a destructive channel where multiple transmissions will garble each other. Our Link-16 multiple access problem differs from the classical problem not only because of our particular objectives, but also because of capture, the LOS channel, and robustness of Link-16 applications. Capture refers to the phenomenon in which, when multiple transmissions arrive, the receiver can receive the one transmitted by the closest unit; despite simultaneous transmissions, messages can still be received. Two geographically distant units can transmit simultaneously without interference; therefore, simultaneous transmissions in Link-16 may be beneficial. To deal with the unavoidable impairments intrinsic to Link-16, such as losses resulting from transmission noise, from the LOS constraint, and from jamming, many Link-16 applications are designed to be robust so that some loss of messages is transparent. Also, Link-16 has mechanisms to retransmit lost messages for applications that require perfect reliability. Whereas restricting the number of transmitters to one is the correct paradigm for the classical problem with destructive channels and with applications that require perfect reliability, the proper objective for our Link-16 multiple access problem is to allow a few select units to transmit simultaneously so that both the robustness of applications and the spatial reuse property of the channel can be exploited.

THE SHUMA DESIGN

Designed to scale and to be consistent with intrinsic Link-16 constraints such as LOS, high transmission noise level, and jamming, the Stochastic Unified Multiple Access (SHUMA) protocol adapts by exploiting information available at the terminal. All Link-16 platforms participate in the Precise Participant Location and Identification (PPLI) Network Participation Group and periodically transmit PPLI messages to inform others of their presence so as to avoid being misidentified as enemy platforms. From received PPLIs, a unit can detect the presence of others and ascertain whether the units share SHUMA time slot pools. SHUMA exploits such information to enable the units to adapt and coordinate without exchanging protocol control messages.

SHUMA allows N_i users to statistically share time slot i, where $1 \le N_i$. A unit j's decision of whether to transmit during time slot i is modulated by probability $p_{i,j} = 1/N_i + (1\text{-}1/N_i)(1\text{-}(1\text{-}1/N_i)^{B_{i,j}})$. Three parameters—$N_i$, $B_{i,j}$, and $K_{i,j}$—suffice to determine this probability and to decide whether to access the time slot. The value of N_i is determined dynamically from received PPLIs; the value of $B_{i,j}$ is calculated by monitoring unit j's own traffic; and the value for $K_{i,j}$ is static and is assigned. SHUMA is specified in Figure 1. (The local variable $X_{i,j}$ is defined such that $X_{i,j} = 1$ if unit j has a message to transmit and $X_{i,j} = 0$ otherwise.)

If each of the N_i units always has a message to transmit and transmits it with probability p, then the probability γ that exactly one unit would transmit is $N_i p(1\text{-}p)^{N_i\text{-}1}$. The choice p^* that maximizes γ is $p^* = 1/N_i$ and is intuitively satisfying because with $p^* = 1/N_i$ the expected number of transmissions is $N_i p^* = 1$. Step B of SHUMA, transmitting with probability $1/N_i$, maximizes the probability of having a unique transmitter. Steps A and C reduce message delays while maintaining fairness of channel access. During light traffic periods when the transmission need of unit j is minimal, $B_{i,j}$ increases, thereby increasing the transmission probability when unit j's traffic load suddenly increases. $B_{i,j}$ decreases when unit j transmits a message using Step C, thereby preventing the unit from monopolizing the channel. Each unit can access its share of time slots in a way tailored to its transmission needs.

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At reference time 0, set B_{i,j} = 0.
if (X_{i,j} = 0) /*no message to transmit*/
    begin
    (Step A) With probability 1/N_i, increment B_{i,j} by 1 if B_{i,j} is less than K_{i,j}.
    end
else
    begin /*message to transmit*/
    Generate a random number R uniformly distributed between 0 and 1.
    if (R<1/N_i)
        begin
        (Step B) Transmit a message.
        end
    else
        begin
        (Step C)
        Generate a random number R uniformly distributed between 0 and 1.
        If (R <1-(1-1/N_i)^{B_{i,j}})
        Tranmit a message and decrement B_{i,j} by 1.
        end
    end.
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FIGURE 1. SHUMA specification.

EXAMPLE OF USE

We illustrate SHUMA through an example. Under the current approach, time slots are dedicated to units as if they will always be present at the same time and be geographically close to each other. Experience, however, indicates that whether these units will appear is uncertain and that an appreciable portion are likely to be absent. Suppose that under dedicated access the capacity is allocated equally among 100 planned units, that each unit is dedicated *one* time slot per time interval, but that only 50 units appear. Because under SHUMA the channel is statistically shared by only 50 units rather than by 100, each unit on the average can access *two* time slots per interval. Furthermore, these units might form, say, two 25-unit local groups such that each operates as if it were the only group present. Because geographically distant units can transmit simultaneously with only minimal mutual interference, SHUMA can double the effective capacity by exploiting this spatial reuse property. Each unit can now access *four* time slots per interval without significantly increasing interference. In this example, SHUMA can increase fourfold the expected number of transmissions by each unit. SHUMA, therefore, could improve Link-16 throughput.

Unplanned units can share the capacity (dynamic entry) because the other units will scale back their rates of access to accommodate the new entrants. The capacity left behind by exited units and by units that have moved away from the vicinity can be reclaimed (dynamic exit). The remaining units can increase their rates of access. Because capacity can be allocated on a group basis rather than on a per-platform basis, SHUMA can simplify preplanning. SHUMA adapts without relying on the distribution of protocol control messages, thereby bypassing many of the difficulties associated with jamming, LOS constraints, and transmission errors; SHUMA is, therefore, robust. Because SHUMA does not require any control messages, the communication overhead does not increase as the number of units increases. As a result, it can be proved that the throughput of SHUMA is nontrivial even when the number of units is very large. The computational complexity of exercising SHUMA is independent of the number of participants (for example, a unit's decision to access the channel requires at most three logical comparisons, two random number generations, and one addition or subtraction, independent of the number of participating units), so the processing requirement does not increase significantly as the number of units increases. SHUMA is, therefore, scalable. The fact that a few lines suffice to specify the protocol testifies to its simplicity; SHUMA can be implemented in the older Link-16 terminals.

QUEUING DELAYS

SHUMA can also reduce message delays. As an example, consider the case where eight units equally share the channel using the dedicated access approach and the case where the same units share the channel using SHUMA. In both cases, messages are generated at each unit according to the Poisson process. The expected queuing delay, the time between when a message is generated and when it is transmitted, as a function of the normalized load is shown in Figure 2. Under dedicated access, a time slot left idle cannot be reclaimed; such loss of capacity results in very high delays. SHUMA can reclaim a time slot left idle, thereby reducing message queuing delays.

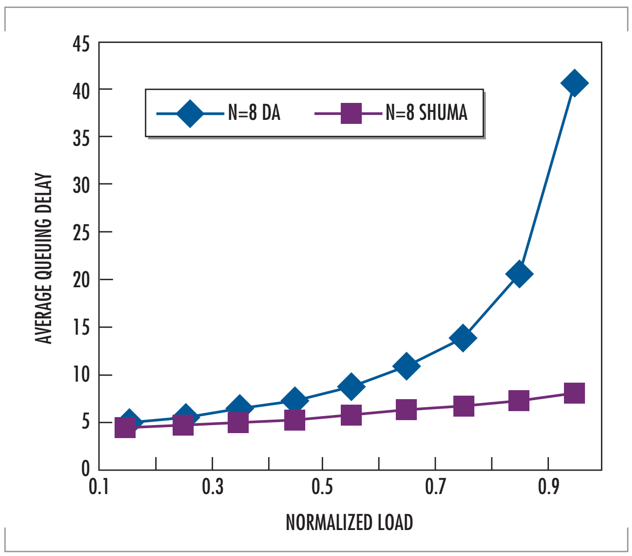

FIGURE 2. Queuing delay.

CONCLUSION

SHUMA is a simple, adaptive, and scalable multiple access protocol designed for Link-16. It simplifies mission preplanning, supports the dynamic entry and exit of Link-16 units, and exploits the statistical nature of traffic and the spatial reuse property of the channel for higher throughput and lower message latency.

Because of its simplicity, flexibility, and scalability, SHUMA holds the promise of improving the effectiveness of Link-16.

Although the Office of Naval Research (ONR) is the sponsor for developing SHUMA, Space and Naval Warfare Systems Command (SPAWAR) PMW 101-159, the Link-16 Program Office, is implementing SHUMA in the Link-16 terminals.

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Current Research: Design and evaluation of networks; stochastic analysis; design and analysis of algorithms.